High-Voltage Generation

Research Project No. FI02.05

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Hydroelectric Research and Technical Services Group
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ABSTRACT

A new method of generation at high voltage may have application at Bureau of Reclamation hydroelectric powerplants. The Hydroelectric Research and Technical Services Group and the Electrical Design Group have researched the benefits and risks as well as the current feasibility of this emerging technology and its applicability to Reclamation. This report addresses engineering design, construction, installation, testing, operation and maintenance, safety, environmental impacts, and power system impacts. It also addresses economic considerations and power customer issues. Conclusions are reached and recommendations made.

DISCLAIMER

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EXECUTIVE SUMMARY

The majority of Bureau of Reclamation (Reclamation) powerplants generate at medium voltage—typically in the range of 6.9 kV to 16 kV. Oil-filled generator step-up transformers and medium-voltage circuit breakers are used to match the higher power system voltages and to connect the generators to the power system. This arrangement is long standing in the power generation industry and has served Reclamation well. However, problems do exist with this arrangement. Both the step-up transformer and the medium-voltage unit circuit breaker, especially when nearing the end of their useful service lives, are potential points of failure, which risk long and expensive outages. Each device also requires substantial maintenance, including finding increasingly scarce spare parts, to keep the aging equipment in a reliable condition. In addition, the transformer poses an environmental risk from oil spill into the tailwater upon rupture. Finally, the transformer has power losses that reduce overall plant efficiency.

Recently, a method of high-voltage generation has been developed which shows promise in mitigating or even eliminating some of the problems with the conventional powerplant arrangement. The developer, Alstom Power of Sweden has several high-voltage generators (with the trademark name of Powerformer™) in operation or under construction. This new technology replaces traditional windings with a proven high-voltage cable system that promises to increase safety and reliability, reduce capital investment and maintenance costs, reduce environmental risk, and increase efficiency.

Retrofitting some older Reclamation units with high-voltage generators may prove beneficial. Installation and operation of high-voltage generation are not without their challenges. Significant changes would be needed to plant equipment and systems as well as to maintenance practices. In some cases, existing plant structure and power system configuration may preclude the application of high-voltage generators.

To determine the technical and economic feasibility of high-voltage generation and to better understand the application and viability of this new generation technology, Reclamation conducted a research study and invited an interested power customer to shadow this research. This report summarizes the research effort.

This research project has shown that it is feasible to operate high-voltage generators to meet powerplant requirements and power system needs. The economic feasibility of applying high-voltage generators will need to be addressed case by case, given the diverse engineering and economic circumstances existing throughout the organization. A life-cycle economic evaluation will be needed for assessing the key aspects and making a comparison to the alternative, which is traditional generator rewind and transformer/ circuit breaker replacement. Close cooperation between prospective Reclamation users

and the local power marketing administration as well as the control area operator is essential to the successful installation and application of high-voltage generation. Because power customers may provide advance funding, their close involvement in the planning, development, and timing of installation is likewise important.

The conclusion of this research is that use of high-voltage generators at some Reclamation facilities would be technically acceptable and economically beneficial. The report recommends that Reclamation's power managers consider high-voltage generation case by case and that a pilot project be developed to evaluate the effectiveness and future applicability of high-voltage generation at other Reclamation facilities.

A. Accomplishments

This high-voltage generation research has put the Bureau of Reclamation in the forefront in exploring new technologies that may increase powerplant reliability, reduce maintenance costs, and minimize environmental risks. This research has accomplished the following:

- Investigated the emerging and promising technology of high-voltage generation
- Performed an engineering analysis of the viability of high-voltage generation capability as a replacement for conventional generation
- Identified and compared advantages and disadvantages of both high-voltage and conventional generation
- Involved power customers and power marketing administrations
- Identified key economic issues important to implementing a high-voltage generation solution to aging powerplants
- Conducted an economic evaluation case study
- Developed preliminary design concepts for a pilot site
- Identified additional Reclamation potential candidate sites
- Reached conclusions and made recommendations
- Given Reclamation managers conclusive information to make sound decisions regarding rehabilitation of existing generators or installation of new ones.

B. Benefits and Cost Savings

B.1. Benefits

This high-voltage generation research has produced several benefits:

- An alternative to the conventional generator rewind and transformer/circuit breaker replacement option
- An alternative powerplant configuration that promises to be more reliable

- An engineering and economic evaluation of high-voltage generation as compared to conventional rehabilitation
- An evaluation of safety and environmental benefits
- A reasonable and defensible economic basis for choosing either a conventional or a high-voltage generation alternative
- A detailed technical basis for determining the viability of high-voltage generation
- An analysis that minimizes investigation by individual power offices
- An inspection of existing high-voltage generation installations
- A preliminary survey of potential high-voltage generation sites in Reclamation
- An unbiased review of the available information

B.2. Potential Cost Savings

Cost savings are likely for Reclamation power programs where managers elect to implement high-voltage generation at plants with aging generators, transformers, and switchgear. These savings derive from eliminating capital investment in step-up transformers and medium-voltage circuit breakers; reduction in the number of significant outages; increased efficiency; a reduced level of maintenance; reduced safety and environmental risks, and increased reliability. The savings are somewhat offset initially by the need for new, additional equipment and system modifications required by high-voltage generation. Because each installation is unique, specific cost savings must be evaluated case by case to determine an accurate benefit-to-cost ratio.

Although accurate cost estimates are difficult to achieve at this early stage of high-voltage generation development, over a life cycle of 50 years it may be possible to save in the neighborhood of 10 percent of the total capital and operation and maintenance costs for a typical Reclamation hydrogenerator with use of high-voltage generation. A 1-percent increase in operating efficiency and an increase in availability of ancillary services should be feasible in most cases.

It is expected that manufacturing and installation methods will become more economical over time, leading to yet more cost savings.

C. Research Team and Process

In fiscal year (FY) 2001, a team was formed to conduct the research. See table 1.

Table 1.—High-Voltage Generation Research Team

Name	Role/Expertise	Office
Gary D. Osburn, PE	Principal Investigator, Electrical Engineer	Hydroelectric Research and Technical Services Group, Technical Service Center, Denver, Colo.
Bruce Lonnecker, PE	Co-Principal Investigator, Electrical Engineer—Generator design, construction, testing	Hydroelectric Research and Technical Services Group, Technical Service Center, Denver, Colo.
Larry Rossi, PE	Co-Investigator, Electrical Engineer—Generator design, construction, testing	Electrical Design Group, Technical Service Center, Denver, Colo.
Boyd Leuenberger, PE	Co-Investigator, Electrical Engineer—Power system studies, equipment ratings, protective relaying	Electrical Design Group, Technical Service Center, Denver, Colo.
Shawn Patterson, PE	Co-Investigator, Electrical Engineer—Voltage regulators & Excitation systems, power system studies	Hydroelectric Research and Technical Services Group, Technical Service Center, Denver, Colo.
Martin Bauer, PE	Significant Contributor, Electrical Engineer—Generator construction, economic evaluation, system applications	Central Valley Operations Office, Mid Pacific Region, Sacramento, Calif.
Kim Nguyen, PE	Significant Contributor, Civil Engineer & Public Utilities Specialist—Economic analysis	Central Valley Operations Office, Mid Pacific Region, Sacramento, Calif.
Dennis McComb	Significant Contributor, Electrical Engineer—Powerplant O&M, generator construction	Central California Area Office, Mid Pacific Region, Folsom, Calif.
Stanley Chun	Significant Contributor, Mechanical Engineer—Powerplant O&M, generator construction	Central California Area Office, Mid Pacific Region, Folsom, Calif.

In addition to the above Reclamation staff, personnel from the Sacramento Municipal Utility District (SMUD) made important contributions: Ed Roman, PE, Sr. Power

Contract Specialist, and John Wetmore, Electrical Engineer. The Reclamation research team is grateful for their participation.

The research team followed a structured process to complete the research and arrive at conclusions. The process consisted of:

- Literature search resulting in a library of reference material
- Discussions with other utilities considering Powerformer™
- Exposure to the Powerformer™ product and manufacturer through informational meetings with Alstom Power
- Repeated development and exchange of questions and answers with Alstom Power by email and in engineering meetings/conference calls
- Site visit in Sweden to several Powerformer™ installations and to the manufacturer's headquarters
- Economic and technical case studies on Folsom Powerplant
- Site visit to Folsom and SMUD Powerplants with Alstom engineers
- Development of Folsom preliminary design concepts (app. A)

Site visits included powerplants where the research team was able to inspect Powerformers™ in various stages of construction, commissioning, and operation, as noted in table 2.

D. General Comparison of Conventional and High-Voltage Systems

This high-voltage generation research project was initiated to evaluate the technical viability of high-voltage generation technology, assess its potential for use at Reclamation powerplants, to identify the advantages and disadvantages of conventional and high-voltage generation configurations, and to provide some economic, safety, and environmental evaluation guidance. It is important to understand the concepts and advantages/disadvantages of both conventional and high-voltage generation to properly compare these two alternatives.

D.1. Conventional Configuration

Currently, many Reclamation powerplants generate at medium voltage (MV), that is with terminal voltage in the range of 6.9 kV to 16 kV. To match higher power system voltages (HV), it is necessary to "step up" the voltage to power system voltages, such as 115 kV or 230 kV. This is accomplished by oil-filled generator step-up transformers, typically located outside the powerplant. Medium-voltage circuit breakers are used for connecting the generator to the step-up transformers, for circuit isolation, for synchronization, and for fault protection. This arrangement is typical and long-standing in the power generation industry worldwide and has served Reclamation well. Figure 1 shows this arrangement.

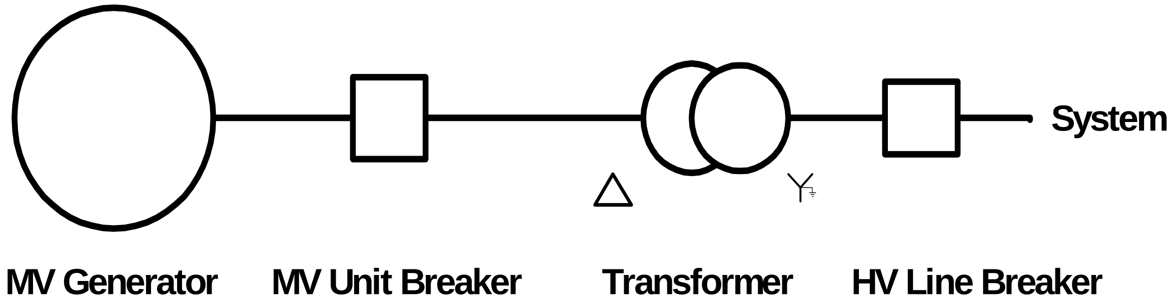

Figure 1.—Conventional Powerplant Configuration.

This arrangement has both advantages and disadvantages:

Advantages: The traditional delta-wye step-up transformer acts as a zero-sequence filter, blocks the injection of disruptive third harmonic frequencies from the generator into the power system, and allows the generator neutral to be grounded (via high impedance in Reclamation plants). Generator neutral grounding helps in suppressing the voltage rise on powerplant equipment to a reasonable level during faults. Protective relaying schemes for this arrangement are standard and common. This configuration also isolates the powerplant from high voltages. The impedance of the step-up transformer reduces the magnitude of fault currents, thus reducing potential damage to equipment. The instrument transformers and surge suppression equipment are relatively compact and are located in the powerplant.

Medium-voltage circuit breakers in Reclamation powerplants are designed for the rugged, start/stop duty of hydroelectric powerplants. The high-voltage breaker on the transmission side of the step-up transformer is not generally rated for this duty and is rarely used except for fault interruption and maintenance isolation. The high-voltage breaker is usually owned by other entities while the medium–voltage breaker is owned by Reclamation. This ownership arrangement establishes a clear line of ownership boudaries and therefore simplifies administration of breaker operation and maintenance.

Disadvantages: Generator step-up transformers are a potential point of failure, and the impacts of failure are generally long term and costly. Transformer replacement time can be as long as 2 years, making lost opportunity generation costs very high, especially if one transformer serves two generators. Large oil-filled power transformers represent a significant investment, requiring regular maintenance and testing, which in itself creates an added annual cost. The impedance of the step-up transformer contributes additional losses to the power system. Waste heat and losses produced in generators and transformers are proportional to the square of the magnitude of the current. Since conventional generators operate with relatively high levels of current, these losses can be significant.

Oil-filled transformers pose risks to the environment. Rupture of the tank or bushing can spill thousands of gallons of insulating oil into adjacent rivers and lakes. Oil burning as a result of high-energy faults pollutes the air. Even routine processing of oil risks some spillage. Disposal of used transformer oil poses its own environmental concerns and costs.

Oil-filled transformers also pose a safety risk. They can fail catastrophically and without warning, potentially ejecting porcelain parts and hot oil. Persons in the vicinity can be injured or killed.

Medium-voltage circuit breakers are also a potential point of failure. A failed breaker can cause a significant forced outage with associated costs. Reclamation medium-voltage unit circuit breakers must be able to survive rugged duty often with multiple openings and closings daily to meet peaking-power demands. This means that regular and thorough maintenance must be accomplished, which usually requires a maintenance outage, special equipment, and specialized training. For many older breakers, spare parts scarcity and high price make maintenance difficult and expensive.

Older circuit breakers, especially of the air-blast type, have been known to explode and cause injury. These breakers are located in the powerplant, where operators and maintenance staff are often present, which poses safety risks. Some circuit breakers are insulated with sulphur hexafloride (SF_6) gas which may produce an added environmental risk from potential leakage and increased costs due to special disposal requirements. Maintenance of SF_6 breakers also requires special safety equipment and precautions.

D.2. High-Voltage Configuration

The high-voltage generation system typically produces electrical power at power system voltages—in the range of 40 kV to 155 kV— thereby eliminating the need for a generator step-up transformer and medium-voltage unit circuit breaker. The high-voltage generator is connected to the power system through the high-voltage circuit breaker, which is used for start/stop duty, synchronizing, and fault protection. This arrangement is shown in figure 2 and has advantages and disadvantages:

Advantages: The step-up transformer and the medium-voltage unit circuit breaker, along with their related costs, losses, maintenance, and safety and environmental risks are eliminated with high-voltage generation. This eliminates the associated capital investment in these items, marginally increases power output, and reduces outage risks. Through the elimination of several potential points of failure, this arrangement promises to make the high-voltage configuration more reliable in the long run.

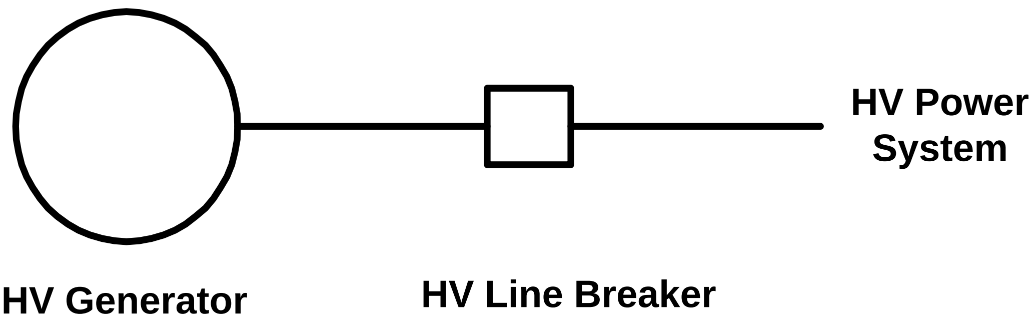

Figure 2.—High-Voltage Powerplant Configuration.

Generator operation at higher (power system) voltages as opposed to medium voltages reduces power losses (I^2R) by lowering generator current. Waste heat and losses produced in generators and transformers are proportional to the square of the magnitude of the current, so the lower operating current of a high-voltage generation system translates to higher operating efficiency.

Disadvantages: The potential disadvantages of converting to high-voltage generation, the impact, and possible solutions are discussed in detail in the sections below. In general, the disadvantages can be categorized as follows:

- Major changes to or elimination of power equipment is required.
- Significant control and protection modifications are required.
- High voltage is introduced into the powerplant.
- High-voltage surge arresters and potential transformers are required.
- Power system grounding must be significantly modified.
- Maintenance practices must be modified significantly.
- Not all powerplants are suitable candidates due to busing configuration and powerplant structure limitations.
- Not all generators are suitable due to power and voltage ratings.

In most cases, there are ways of accommodating these disadvantages.

It is assumed that since there is presently only one supplier of high-voltage generator systems, competitive forces that would otherwise help drive down the cost of the technology could be limited. However, competition may evolve over time and it is recognized that emerging high-voltage technology must compete case by case with conventional technology.

Alternatives: An alternative to a high-voltage generator that operates at power system voltage is a high-voltage generator combined with an autotransformer. The generator would operate at something less than power system voltage and the autotransformer would match the generator voltage to the power system. While this arrangement does not provide all the advantages of eliminating the traditional generator step-up transformer, it may still be beneficial in certain circumstances. For further discussion, see section F.2.1.

E. High-Voltage Generation History and Experience

Currently, Alstom Power of Sweden produces the only known commercially viable high-voltage generator available under the trademarked name of Powerformer™. Alstom holds many key patents to high-voltage generation technology. As a result, much of this high-voltage research has focused on Alstom's experience with Powerformer™.

At the time this research was initiated, Alstom's Powerformer™ at Porjus Powerplant in northern Sweden was the only operating high-voltage hydrogenerator in existence. Several other Powerformer™s have been commissioned or are in construction. Of particular interest is the recent commissioning of the Porsi unit, which has ratings compatible with many Reclamation generators. No Powerformers™ currently exist in North America. Table 2 outlines the current status of Powerformer™ installations.

It should be noted that most existing applications of Powerformer™ are in hydroelectric powerplants. Alstom has demonstrated that Powerformer™ technology is suitable for retrofitting some existing installations. The operating history of Powerformer™ is limited, and thus long-term viability assessment is based solely on extensive laboratory testing by the manufacturer. However, the operating history thus far indicates no serious problems related to high-voltage generation technology itself.

Name	Type	MVA /pf	kV	rpm	Excitation	Owner	Location	Oper. Date
Porjus U9*	Hydro	11/ 0.9	45	600	Brushless	Porjus Hydro Power Foundation	Lule River Northern Sweden	June 1998
Eskilstuna	Thermal	42/ 0.9	136	3000	Brushless	Eskilstuna Energi	Sweden	December 2000
Porsi*	Hydro	75/ 1.0	155	125	Brushless	Vattenfall	Northern Sweden	May 2001
Holjebro*	Hydro	25/ 0.95	78	115.4	Brushless	Fortum Energy	Central Sweden	June 2001
Miller Creek	Hydro	30/ 0.93	25	720	Brushless	EPCOR Power Develop Corp.	British Columbia	Order placed May 2001
Katsurazawa	Hydro	9.0/ 0.93	69	428	Brushless	EPDC	Japan	Order placed May 2001

Table 2.—Powerformers™ in Operation and Construction January 2002

* Inspected during High-Voltage Generation Research project

F. Technical Feasibility Evaluation

F.1. Generation Equipment Evaluation

F.1.1. Generator Stator and Armature Winding

The generator stator structure and the armature winding will be the most affected components when conventional generators are retrofitted with high-voltage generators. Major components will be removed and discarded, while new assemblies will be constructed and installed.

The discussion in this section is based on analysis of Alstom Power's Powerformer™ product.

Conventional Generators

All Reclamation hydroelectric generator stators consist of a frame, core, air coolers, and armature winding. The frame supports the core; coolers; armature winding; and, in most Reclamation plants, the thrust and upper guide bearings. The stator is enclosed in an air housing. The core, which is built up of thin steel plates, concentrates the magnetic field emanating from the generator rotor to produce an induced current in the armature winding. The armature winding, comprised of a series of coils, fits into an average of 200 slots in the core and carries the generator current. Heat, produced mostly by current flowing through the winding, is dissipated to air circulating through the core and rotor and removed by air-to-water coolers mounted on the outside of the frame. The air-to-water coolers are generally in an open system with the water supply provided directly from the reservoir and discharged to the tailrace.

The armature winding coils in Reclamation generators have a rectangular cross section and are formed with multiple strands of copper wire surrounded by insulating material. Each identical coil develops a voltage. As series circuits of identical coils are connected, voltages are added until the terminal voltage is achieved. Many older Reclamation generators still have insulating material composed of asphalt, asbestos and mica. Newer insulating materials, available since the late 1960's include epoxy or polyester and mica. The newer insulating materials provide higher insulation capacity than the older types but still are limited to an electrical stress of about 3 kilovolts per millimeter of thickness. Since space in the core slots is limited, insulation around the copper conductors can be no more than about 3 to 5 millimeters thick. For this reason, the terminal voltage of conventional hydrogenerators is limited to about 16,000 volts, phase-to-phase.

High-Voltage Generators

High-voltage cable insulation technology has evolved to withstand an electrical stress of 10 kilovolts per millimeter. Alstom has developed a generator design that uses power cable to replace the armature winding of the conventional generator stator.

With Powerformer™, the new winding is cross-linked polyethylene (XLPE) cable. This winding has many more turns than a conventional winding, thus adding to a higher terminal voltage. The stator will typically be higher than for the conventional machine in order to accommodate the longer end-turns of the winding.

Since the winding, or cable, of the Powerformer™ is of circular cross section, the core slots have ridges that make space for, as well as retain, the cable. See figure 3. This new slot geometry allows for insulation as thick as 15 millimeters for certain generators. The combination of higher insulation stress (10–15 kV/mm) and thicker insulation (5–15 mm)

Figure 3.—Powerformer™ Core (Photo courtesy of Alstom Power).

provides the capability to build a generator that operates at a higher (power system) voltage (150 kV).

The cable insulation thickness is typically increased in steps by using different cable sections that are interconnected with splices. This is done to provide a higher insulation level at the high-voltage terminal ends of the windings as the voltage in the series circuit increases with the length from the machine neutral.

XLPE cables have been widely used for quite some time in the power industry and are well proven to be able to withstand the voltages needed for high-voltage generation. Currently, the proven capability of high-voltage hydrogenerators is 75 MVA at 155 kV, well within the range of many Reclamation generators. Theoretically, Powerformer™ can produce power at higher than 230 kV. Review of the design data for Folsom reinforces the statements by Alstom that while Powerformer™ could be applied at Folsom to generate at 230 kV, the losses would render that application uneconomical. This is due to core losses, since the copper is farther away from the core with the thicker insulation.

High terminal voltage means lower current for the same power output, so less waste heat (proportional to the square of the current) is produced with high-voltage generation. The heat is removed, not with air coolers as in a conventional machine, but by direct cooling of the stator core. This is accomplished by means of cooling water passing through plastic tubing threaded through special holes in the stator core.

Construction and Installation.—Because there are more series cable coils in the armature winding, Powerformer™ typically requires a larger diameter stator core with new, deeper slots. For this reason, the core, stator frame, and air housing must be replaced when changing from a conventional hydroelectric generator to a Powerformer™.

The end turn portion of the winding (cable) that extends out of the core top and bottom (vertical hydrogenerators) of the Powerformer™, is much longer because the cable cannot be formed to tight bends like the conventional windings. See figure 4. For this reason, the Powerformer™ is taller than the conventional generator it replaces. The number of turns needed to achieve the appropriate voltage also requires a deeper slot than in conventional generators. This results in a larger diameter for the Powerformer™ frame and air housing.

The frame and core of the Powerformer™ are installed in the same fashion as with the conventional generator, that is, by stacking the core plates on a frame. The Powerformer™ winding is installed in a very different process. For conventional machines, the individual coils are pressed into the slots of the core, retained with springs and/or rigid wedges, and brazed to others in the string to form an electrical circuit.

For Powerformers™, the cable is repeatedly threaded through the core from each end. The cables are retained in place by inserting plastic tube wedges between the cables and filling the tubes with elastomer. A single section of cable may be looped through the core as many as 50 times, with a splice box at each end. This results in a stator winding with fewer connections than required for conventional machines. Splice boxes are shielded connections between the cable sections. Each connection consists of specially designed ferrules that are crimped using a pneumatic tool to ensure that cable strands are compressed to the appropriate pressure without damage.

Significant plant space is required during installation of the cable in the core, and this requirement should be reviewed closely for any retrofit application. Plant space must be available for locating the cable reels, for laying out the cable, and for pulley reels above/below the core for looping the cables through the core. In the Folsom Powerplant case study, it was noted that the best place to facilitate this installation was outside of the plant on the plant deck, and then the completed unit could be lowered through hatch covers, into the plant.

Figure 4.—Powerformer™ End Turns (Photo Courtesy of Alstom Power)

The need for modification of associated equipment, such as the bearings and shaft, while less likely, will have to be determined individually for each retrofit.

Because of the additional height and corresponding weight of the stator, it is important that the powerplant crane height and lift capability be evaluated to ensure in advance that the machine stator can be lifted into place after assembly.

Testing.—Proof testing, or high potential (high voltage) testing, using externally applied voltage cannot be performed on an assembled Powerformer™ as for conventional machines. The reason is that along the path of the Powerformer™ winding from neutral to terminal ends, the induced voltages of normal operation gradually increase, while the electrical insulation thickness typically increases in corresponding steps. Testing the winding at or above terminal voltage, as is done on conventional Reclamation windings, would overstress the portion near the neutral end.

As an alternative to high-voltage testing, Powerformer™ cable is tested to AEIC standards. For example, 115-kV cable is tested at 140 percent of rated voltage for 30 minutes. Once installed, each phase in turn is grounded at the neutral end, and the machine is rotated and self-energized until the terminal voltage of the phase is raised to 173 percent of rated voltage for a predetermined period of time.

Life Expectancy.—Depending on insulation type, maintenance philosophies, and operating conditions (e.g., thermal cycling), winding life expectancy for conventional machines is generally accepted to be about 30 years. When the insulation deteriorates, the winding is replaced but the frame is typically retained. Core material must be replaced, depending on insulation types, about every 50 years for older machines but cores of new machines are expected to last somewhat longer. The magnetic characteristics of new core material are so much better than those of the original material that cores are often replaced before their expected life has elapsed, to improve machine efficiency.

Depending on service conditions, Powerformer™ winding (cable) is expected to last a minimum of 50 years. Power cables used as generator winding material have not been in service for more than 2 years of continuous use; therefore, life expectancy prediction is based on underground cable experience and accelerated life reduction testing. Accelerated life tests have shown that these cables should survive 64 years at rated condition without significant change in electrical breakdown strength.

Based on the information provided by the manufacturer, it appears that the cable winding should have longer life when compared to conventional windings. The manufacturing process for the cables is tightly controlled, which leaves little room for defects. By contrast, conventional-coil manufacturing has numerous steps requiring manual installation of taping systems, which can lead to defects or differences in the insulating quality.

Operation.—Operationally, high-voltage generators and conventional machines are expected to be very similar. Some short-term overload capability in excess of conventional machines appears achievable for Powerformer™. Otherwise, starting, stopping, and loading and unloading procedures should be very similar to those of conventional machines.

Maintenance.—Maintenance and condition testing of Reclamation's conventional generator windings is well established and documented. Since in-service experience with Powerformer™ cables is very limited, it will be important to perform additional testing and condition monitoring throughout the operating life of the units. Certain aspects of Powerformer™ operation and maintenance can only be verified with long-term monitoring. The manufacturer has installed significant diagnostic instrumentation on Unit 9 at the Porjus powerplant to verify performance of the Powerformer™. A monitoring, maintenance, and testing program based on the manufacturer's recommendations and Reclamation experience will be important. Partial discharge equipment can be installed permanently in the machine so that cable condition can be satisfactorily monitored during operation to provide additional information and early warning of incipient faults. Some maintenance and testing activities will change with implementation of high-voltage windings. During this research, an evaluation was made comparing existing to proposed maintenance and testing procedures; it was determined that new methods would satisfactorily meet the needs of the high-voltage generator and are within the capabilities of the powerplant O&M staff.

Safety.—Use of a high-voltage generator will introduce high voltages into the powerplant. This should not be a problem from the perspective of equipment ratings since appropriate spacing and insulation will be provided. Proper safety practices, including use of the Reclamation Hazardous Energy Control Program, will provide adequate protection for operation and maintenance personnel. Electric fields produced by high-voltage generation can be adequately shielded, and the reduced current levels from high-voltage generation will create significantly lower magnetic fields.

Environmental.—The reduced environmental impacts resulting from elimination of the step-up transformer will be significant, as a major oil-containing device, the step-up transformer, will be eliminated. If an autotransformer is used, it can be located in the switchyard, thus reducing the risk of an oil spill contaminating the tailwater. The longer life expectancy of the Powerformer™ cable winding will reduce the frequency of winding replacements and thereby reduce the associated disposal problems. Disposal of step-up transformer oil and insulation material is eliminated.

Spare Parts.—Spare winding components are typically stocked for conventional windings; conversely, limited amounts of spare cable will need to be stocked for Powerformer™. It should be noted that the cables are manufactured for each machine. Cables for machines with different dimensions or ratings will not be interchangeable with other machines. It may be beneficial to stock a few hundred feet of spare cable for minor cable-end repairs. Major supplies would have to be acquired from the manufacturer at the time of rewind or major overhaul. Spare splice components should be acquired at time of purchase. Acquiring spare parts for high-voltage generators in a timely manner is not considered to be a significant issue.

Issues and Concerns.—Because the stator in the Powerformer™ will be taller than in the conventional machine that is being retrofitted, clearances and lifting capacity of the powerplant crane must be evaluated.

Reclamation stator testing methods will require reconsideration in light of the limitations of testing cable windings.

A concern with the installation of high-voltage generators is the limited operational experience to date and the life of the core and stator winding in such an environment. Early experience with high-voltage generation is encouraging but it is expected, as with conventional units, problems often do not become known for many years. It is possible that unforseen problems with the cable winding or new core may occur many years down the road. This concern should be balanced against recent Reclamation uprate and rewind history where even supposedly well-proven conventional windings have proven less than satisfactory.

The research shows that the Powerformer™ manufacturer has been very diligent in identifying potential risks, designing to eliminate them, and testing to verify longevity. Some concerns are:

- Failure modes of cable splices and ease of repair
- Expected life in actual operation
- Unknown modes of failure

These risks appear to be manageable and not out of line with known risks of conventional windings.

F.1.2. Generator Rotor and Field Winding

The purpose and use of the generator rotor and field winding (providing a moving magnetic field) will not change with the application of high-voltage generation.

Conventional Generators

The rotors of hydroelectric generators in Reclamation facilities are of the salient-pole type, characterized by distinct rotor poles that are usually keyed onto the circumference of the rotor rim. The magnetic flux produced by the rotor field is coupled with the stationary armature winding to convert the rotating mechanical energy produced by the turbine into electrical energy.

The components of the generator rotor and field winding consist of the structural rotor body components, the rotor spider and rim; and the electrical components, the field poles, the field amortisseur,[1] and the collector rings. The windings on each field pole are connected in series to form the field winding, and then the leads are routed out to the collector rings. Excitation is supplied to the collector rings from shaft-mounted rotating exciters or through solid-state excitation systems.

[1] The amortisseur winding is installed on the field pole face to suppress hunting, improve balance of terminal voltage, and reduce harmonic distortion.

High-Voltage Generators

The generator rotor and field winding will most likely be affected when retrofitting for a high-voltage generator application. Because of the Powerformer™ stator winding construction, the stator core height and probably the diameter will be greater for a Powerformer™ application as noted in section F.1.1. The rotor field poles and rim must be redesigned accordingly (possibly increased in height) to ensure optimum magnetic coupling between the rotor field and the stator winding.

Modifications required will vary for each machine and must be studied carefully by the high-voltage generator manufacturer to optimize each machine's design while maintaining desired machine characteristics. In some cases, the existing rotor may only need minor modifications (e.g., new rotor poles, rim, and fans). In other cases, the entire rotor rim, spider, and poles may need replacement to match the new stator dimensions. No collector rings are required for units using brushless excitation systems such as are typically provided with Powerformer™. Powerformer™ may require less field current to achieve the rated output. This will allow reuse of the existing collector rings if it is not desirable to use a brushless excitation system

The fan system of the rotor will also need to be altered. The changes include new blades and baffles.

Acceptance Testing.—There appears to be no reason that manufacturer and Reclamation acceptance testing methods should be any different from current practices.

Life Expectancy.—Since high-voltage generator rotor and field winding construction, operation, and maintenance are similar to those of conventional units, life expectancy should be similar to that of conventional generators.

Maintenance and Testing.—The use of a high-voltage generator should not require modification of current rotor and field maintenance and testing practices. If Powerformer™ is provided with brushless excitation, brush maintenance will be eliminated.

Safety And Environmental.—No additional impacts on safety or the environment are expected from the rotor or field winding as compared to conventional generators.

Issues And Concerns.—Because the rotor may be heavier and taller in the high-voltage generator than in the conventional machine, clearances and lifting capacity of the powerplant crane must be evaluated.

F.1.3. Voltage Regulator and Exciter

Both Conventional and High-Voltage Generators

Theory.—Essentially, voltage regulator and exciter design and construction are not affected when applying high-voltage generation. The field voltage and current required are of the same order of magnitude as those for the conventional configuration.

The "standard" Reclamation exciter (new or replacement) is a fully static system, while existing Powerformer™ installations incorporate brushless rotating exciters. Reclamation use of a brushless exciter does not appear to pose a problem, since acceptable system response, voltage ceiling, and control features such as a power system stabilizer (PSS) can be provided. Alstom also is able to provide a static exciter if one is specified.

Design, Construction, and Installation.—Since the opportunity to apply high-voltage generation technology often comes at a time when the excitation system is at or past its useful life expectancy, replacement of the excitation system is warranted as a part of the machine overhaul. Extensive reconstruction of the generator to apply high-voltage generation will likely require dismantling of the excitation system, especially if a rotating exciter is still in use, which is another reason to consider complete replacement of the excitation system.

Testing, Life Expectancy, O&m, Safety, and Environmental.—No difference from the conventional configuration is anticipated.

Issues And Concerns.—None.

F.2. Associated Equipment Evaluation

F.2.1. Generator Step-Up Transformer

Conventional Generation

Theory.—The generator step-up transformer is required in the conventional (medium-voltage) configuration to increase the voltage to power system levels. The transformer also prevents injection of third harmonic frequencies into the power system and provides a point of system grounding.

Construction and Installation.—The step-up transformer is generally installed on the transformer deck over the tailwater, or in the powerplant. In either case, moving the transformer is cumbersome, making replacement somewhat difficult. However, space is typically adequate for the replacement transformer and all connections are available.

Operation and Maintenance.—Standard Reclamation practices apply and are well understood.

Safety.—The step-up transformer presents risk of catastrophic failure and explosion. Shrapnel and burning oil are safety risks to personnel and the public.

Environmental.—The step-up transformer contains large volumes of insulating oil that can leak into the soil under normal operation, or be spilled into the tailwater or burned into the atmosphere during catastrophic failure.

Issues and Concerns.—Reclamation use of step-up transformers has accommodated the associated risks and costs, which could be reduced or eliminated with high-voltage generation.

High-Voltage Generation

Theory.—High-voltage generation generally does not require a transformer to step up from medium voltage to power system voltage, because the generator produces power at this higher voltage. However, in some applications, efficiency can be improved and costs reduced by choosing the optimum generation voltage and adding an autotransformer to bring the generator voltage to power system levels. Some advantages of this approach are:

- An autotransformer typically will cost less and have lower losses than a step-up transformer.
- A tertiary winding on the autotransformer can be a source of station service power.
- An autotransformer can provide a point of system grounding that is unavailable with the high-voltage generator arrangement without an autotransformer.
- An autotransformer can be located remotely from the powerplant, which can improve safety and reduce environmental risks.
- It may make it more feasible to retrofit an existing machine, since the high-voltage generator is smaller if an autotransformer is used.

Construction and Installation.—Implementing high-voltage generation will require the retirement of the step-up transformer. Likely, the transformer will be removed and disposed of and the space used for the high-voltage surge arresters. Removal of the transformer will impact the auxiliary power system and the control/protection/indication/metering systems as well. Also impacted will be the fire suppression (i.e., water deluge) system, which will be eliminated for the affected unit. Transformer insulating oil storage, processing, and containment systems will no longer be required for that transformer (but may need to be retained for other transformers). Likewise, transformer cooling water piping and auxiliary power requirements will likely be eliminated.

If an autotransformer is used, switchyard installation typically is more convenient than at the powerplant; in some cases, this may require approval and coordination with other entities that may own the switchyard.

Operation and Maintenance.—On-site and remote operator observations and tasks associated with the step-up transformer will be eliminated. All maintenance activities (and costs) associated with the step-up transformer will be eliminated. Step-up transformer testing activities will be eliminated as well as the need for spare parts. Some maintenance activities will be required for new surge arresters.

If an autotransformer is used, operation and maintenance is similar to that for step-up transformers.

The effect of transformer impedance, grounding, and third-harmonic blocking are addressed in other sections of this document.

Safety.—Safety concerns related to the step-up transformer will be reduced and smaller risks associated with surge arresters will be assumed. Potential fire risks associated with oil in a transformer or in storage will be eliminated. Transformer explosion risk will be eliminated. Associated risks to personnel and the public due to energized transformers will be less of a concern with the elimination of the step-up transformer. Risk to personnel conducting transformer testing will be eliminated, as well.

An autotransformer located in a switchyard is safer than an oil-filled step-up transformer located at the powerplant. There is less risk to personnel and the public from catastrophic failure.

Environmental.—Elimination of the step-up transformer will remove the risk from oil spill or burning oil due to tank or bushing rupture. Also, spills occurring during oil processing and storage will no longer be an issue, as removing the step-up transformer will eliminate oil handling. Elimination of the step-up transformer will also remove the need for oil-spill-containment systems.

An autotransformer located in the switchyard presents less risk of oil spills contaminating tailwater upon tank rupture.

Issues and Concerns.—None that are not addressed in other sections.

F.2.2. Switchgear and Buswork

Conventional Generation
Medium-Voltage Switchgear and Buswork

The generator medium-voltage circuit breaker is necessary for protection, isolation, and synchronizing in the conventional (medium-voltage) configuration. The medium-voltage buswork connects the generator to the medium-voltage breaker and the breaker to the step-up transformer. For conventional rehabilitation (i.e., replacement in-kind, not high-voltage retrofit), the medium-voltage circuit breaker would be replaced or rehabilitated while the buswork would be retained.

High-Voltage Generation
High-Voltage Switchgear and Buswork

Theory.—The medium-voltage breaker and buswork are no longer needed in the high-voltage configuration. The high-voltage breaker will provide switching and fault protection. High-voltage buswork will be required to connect the high-voltage generator to the high-voltage breaker.

Design.—High-voltage generation requires one high-voltage circuit breaker for each generator so that synchronizing the generator to the power system can be accomplished. The existing high-voltage breaker must be evaluated to see if it is capable of the duty associated with unit control, synchronizing, and protection that will be expected. The breaker must be suitable for more frequent operation once the medium-voltage breaker is removed.

It may be possible to use the existing breaker, or it may be necessary to replace it with one more suitable. Generally, the high-voltage breaker is located in the switchyard separately from the plant. At plants where generating units are bused together at medium-voltage, it may be possible to locate the new high-voltage breaker in the location of the removed step-up transformer at the plant.

Construction And Installation.—Implementing high-voltage generation will require the retirement of the medium-voltage circuit breaker and associated disconnect switches, grounding switches, instrument transformers, surge arresters, and buswork. Removal of the circuit breaker will have impacts on the auxiliary power system and the control/protection/indication/metering systems, as well. Buswork removal will be necessary from the generator through to the now-unnecessary step-up transformer. Buswork cooling systems will no longer be necessary. New high-voltage potential transformers added for metering and relaying are covered in another section of this document. High-voltage buswork also will have to be added to connect the high-voltage generator to the high-voltage circuit breaker. Any construction and installation issues must be coordinated with the high-voltage breaker owner, which may not be Reclamation.

Operation.—Operating the high-voltage breaker as the unit breaker will be similar to operation of the medium-voltage breaker but will require close cooperation with the breaker owner. Operations staff will have to be trained appropriately. The effects of control and protection changes caused by elimination of the medium-voltage breaker are addressed in other sections of this document.

Maintenance.—All maintenance activities and related costs associated with the affected medium-voltage class unit breaker will be eliminated. Medium-voltage breaker testing will be eliminated as well as the need for spare parts. High-voltage breaker maintenance is likely to increase as the breaker is used more frequently. Maintenance is likely conducted by the breaker owner (although this is sometimes contracted to Reclamation). Should Reclamation assume breaker maintenance, adequate training will be required. Maintenance for high-voltage buswork will be similar to that for medium voltage, depending on switchgear type.

Safety.—Safety risks associated with medium-voltage circuit breaker maintenance and testing will be eliminated. The introduction of high-voltage buswork in the powerplant should pose no undue risk. Design and construction will address safe clearance issues. Risk from electrical and magnetic fields is negligible. Maintenance is not allowed on energized equipment at any voltage level in Reclamation. Risk of in-plant explosion of air-blast circuit breakers and release of toxic byproducts of SF_6 breakers will be eliminated.

Environmental.—Elimination of the medium-voltage circuit breaker will eliminate the risk from SF_6 gas escape where such breakers are used.

Issues and Concerns.—The high-voltage breaker in many cases is owned, maintained, and operated by others such as the power marketing administration (PMA). Also, the breaker may not be suitable for the frequent operating requirements and thus may need to be replaced with a more rugged type. If the breaker needs to be replaced, this will affect the cost of this alternative. The PMA must be part of the decisionmaking process that leads to the high-voltage breaker being used in this new manner and in any replacement decisions.

Also, application of high-voltage generation at any facility where multiple generators share one transformer, will increase the number of high-voltage circuit breakers needed.

F.2.3. Instrument Transformers

The purpose of instrument transformers is to provide voltage and current references for relaying, metering, and synchronizing. Instrument transformers convert higher currents and voltages to lower values safe for use in these protective, indication, and control systems.

Conventional Generation

Theory.—Instrument transformers include current and potential transformers located in the following areas in conventional generator configurations:

Current transformers:	Neutral of generator split-phase windings Neutral of generator main windings Line-side of generator main windings Both sides of the medium-voltage circuit breaker Both sides of the generator step-up transformer Both sides of the high-voltage circuit breaker
Potential transformers:	Near generator terminals or medium-voltage circuit breaker On power system side of high-voltage circuit breaker Generator neutral grounding transformer

High-Voltage Generation

Theory.—It is obvious that with the elimination of the step-up transformer and medium-voltage circuit breaker and the increased voltage of the generators, many of these instrument transformers will be eliminated and others replaced with high-voltage counterparts. The neutral grounding transformer is completely eliminated, since the neutral of the high-voltage generator is operated ungrounded.

Design, Construction, and Installation.—Current transformers in the high-voltage generator will be designed and installed as part of the generator installation. In some cases, voltage ratings will have to be compatible with the higher voltage, while current ratings will reflect lower stator currents. It is not necessary to apply high-voltage-rated current transformers in all high-voltage locations, since the generator cable itself is insulated. Split-phase current transformers will not be replicated in the high-voltage generator, since there are no split-phase windings.

New high-voltage potential transformers will be required. Capacitively coupled voltage transformers may not be suitable in the ungrounded Powerformer™ arrangement—fully inductive potential transformers may be necessary. Also, it may be necessary to apply two sets of transformers in order to achieve the recommended protective relay redundancy. In higher voltages, these potential transformers will have to be oil filled and most likely located outside the powerplant. It may be possible to locate these potential transformers in the vacant location left by step-up transformer removal.

The elimination and addition of instrument transformers will have significant impact on secondary circuit cabling, which is addressed in section F.2.6 of this document.

A preliminary design for instrument transformers for a high-voltage generator at Folsom Powerplant is included in appendix A.

Testing and O&M.—Some Reclamation offices do not have current experience in testing and maintaining high-voltage instrument transformers. However, tools and training are readily available.

Safety And Environmental.—Safety related to high-voltage instrument transformers should not be a concern provided that all appropriate operation and maintenance practices are followed. Minimal increased environmental risk from the introduction of oil-filled potential transformers is more than offset by the elimination of the oil-filled step-up transformer, which has greater quantities of oil.

Issues and Concerns.—None.

F.2.4. Protective Relaying

The purpose of protective relaying is to protect equipment from abnormal operating conditions such as over/under voltage, overcurrent, and ground faults. Protective relay schemes are specific to the equipment and configuration found at each facility. The generator stator and rotor, step-up transformer, medium-voltage circuit breaker, and connecting buswork are all components that are protected by relaying systems. Since these components will change in a high-voltage generator configuration, the protective relaying will also change.

Conventional Generation

At Reclamation facilities, typical electrical protective relaying can be summarized as follows:

Generator stator protection:	Split-phase differential (87GS)
	Stator winding differential (87GD)
	Stator ground (64GP)
	Stator high temperature (49GP)
	Stator overvoltage (59GP)
	Stator overcurrent (50/51GP)
	Loss of field (40GP)
Generator rotor/field protection:	Negative sequence (46GP)
	Field overvoltage (59E)
	Field overcurrent (50/51E)
	Field ground (64F)

Transformer protection:	Volts per hertz (59/81 or 24) Transformer differential (87KD) Transformer ground overcurrent (51KG)

Circuit breaker protection and medium-voltage buswork protection is generally incorporated in the above relaying. Circuit breaker protection is supplemented with breaker failure relaying at many plants. High-voltage buswork protection is often provided by distance relays in the switchyard or, occasionally by differential relaying. High-voltage circuit breaker protection is included in switchyard bus protection schemes and supplemented with breaker failure.

Existing Reclamation protective relaying systems are not generally redundant. However, the above relaying does provide backup protection in case of failure of one type of protection.

High-Voltage Generation

Obviously, there will be no need to provide protection for the nonexistent medium-voltage breaker and step-up transformer with a high-voltage generator. Likewise, there are no split-phase windings in a Powerformer™. In addition, the traditional method of protecting generators from ground faults will not be possible but ground fault protection can and should be provided. During normal operation, ground fault current may be substantial, since the Powerformer™ will be connected directly to the system. However, prior to synchronization, the unit is isolated from all grounds so special protection from ground faults will be necessary. In addition, from the system perspective, the available ground fault current may be substantially reduced; however, ground fault protection is still recommended.

Adequate protection for the high-voltage generator, buswork, and high-voltage circuit breaker can be achieved with a new relaying scheme. Alstom Power recommends a redundant level of protection for Powerformer™, believing that the added expense is justified by the reduced risk. Digital package relays are recommended by Alstom and can be provided along with the Powerformer™.

Appendix A includes a preliminary design for protective relaying for a high-voltage generator at Folsom Powerplant.

Construction, Installation, Testing, and O&M.—Existing relays will need to be removed and replaced with new package relays. This is a significant effort and will require changes to the control boards. Testing and maintenance is the same as for any new relay system.

Safety and Environmental.—There are no safety or environmental concerns related to protective relaying.

Issues and Concerns.—None.

F.2.5. Surge Protection Equipment

The purpose of surge protection is to protect equipment from abnormal voltages, such as transients due to lightning strikes, switching operations, etc.

The amount of insulation on the windings of a generator is limited by space. As a consequence, the voltage stresses between turns and between the conductor and ground must be examined and the appropriate counter-measures taken to prevent failure in the event of a voltage transient.

Conventional Generation

Turn-to-Turn Insulation.—The multi-turn method of winding construction results in large capacitance and inductance throughout the winding. This results in very low surge velocities of transient waveforms experienced in the windings. As a consequence, the windings are vulnerable to fast-front (fast rate of rise) waves. When a fast-front surge voltage wave strikes the winding, it will be distributed over the one or two turns closest to the machine terminals and therefore results in a very high voltage between these turns. Installation of a surge capacitor on the machine terminals to “slow down” the voltage wave and increase the rise time provides protection for the conventional generator.

Conductor-to-Ground Insulation.—There is limited insulation between the conductors and ground due to the limited space. The stress on the insulation to ground is a function of the magnitude of the surge voltage. Therefore, surge arresters are added to the machine terminals to limit the magnitude of the surge voltage wave to protect the machine.

High-Voltage Generation

Turn-to-Turn Insulation.—Powerformer™ does not have multiple turns within a single coil of the winding, as is possible in the conventional generator. Instead, each “turn” of the winding is isolated in a separate groove within a slot of the stator core. The cable surfaces do contact each other at the end-winding portion of the stator. From a surge protection standpoint, the insulated solid dielectric cable system has two advantages. One: the cable insulation thickness is significantly greater than the thickness between turns of a conventional generator, and thus failure between turns is extremely unlikely. Two: a cable system has enough capacitance to eliminate the need for a separate surge capacitor.

Conductor-to-Ground Insulation.—Although the insulation to ground has been improved by the cable design, this is still an area of weakness. Therefore, surge arresters are still necessary to protect against large magnitude voltage surges.

Neutral Protection.—The neutral of the Powerformer™ is left ungrounded to prevent the generation of third harmonic currents. Unfortunately, for an ungrounded machine, large transient voltages harmful to the insulation can appear on the machine neutral. To resolve this problem, a surge arrester is connected from the Powerformer™ neutral to ground.

All line-side surge arresters associated with the Powerformer™ must be selected based on full line-to-line voltage. This is because prior to synchronization, the Powerformer™ is insulated from the system ground, and the maximum voltage during a fault could approach full line-to-line voltage. A study will be necessary to determine the optimum rating for the neutral arrester, however the rating will be between line-to-neutral and line-to-line voltages.

Design, Construction, and Installation.—Existing medium-voltage surge arresters will be removed and discarded. High-voltage surge arresters will be installed in such a location as to provide maximum protection for the generator winding. It may be possible to locate these surge arresters in the vacancy left by step-up transformer removal.

Testing and O&M.—Some Reclamation offices do not have current experience in testing and maintaining high-voltage surge arresters. However, tools and practices are readily available.

Safety and Environmental.—Safety related to high-voltage surge arresters should not be a concern, provided that all appropriate operation and maintenance practices are followed.

Issues and Concerns.—None

F.2.6. Controls and Auxiliary Power

For purposes of this document, "controls" will include the control, protection, metering, instrumentation, and alarm systems that are affected by high-voltage generation. Auxiliary power systems are the ac and dc systems that are required to make major equipment function.

Modifications Required for Conversion from Conventional to High-Voltage Generation

Theory.—Due to the elimination of the step-up transformer and medium-voltage unit breaker as well as the rearrangement of the instrument transformers, significant changes must be made to the control and auxiliary power systems. Also, control changes will likely be required to accommodate replacement of the generator and exciter.

Design.—New design (electrical schematics and wiring diagrams) will be required, and revised single-line and switching diagrams will be necessary. A study of equipment ratings and power system studies, as well as new relay settings for the revised protection scheme will also be needed.

Circuit Breaker Control and Indication.—Breaker opening and closing functions must be shifted from the medium-voltage unit breaker to the high-voltage breaker. Since the high-voltage breaker is usually located in the switchyard, this may pose some difficulty, unless breaker control is already available in the powerplant. In many cases, the high-voltage circuit breaker is owned and operated by others, such as the power marketing administration. This means close collaboration in the design and construction phases is required.

Synchronization.—Redesigned synchronization circuits will now control the high-voltage circuit breaker. Suitable potential transformers must be available, as well as circuit breaker control circuits. Since out-of-step synchronizing could be more damaging for a high-voltage generator with no step-up transformer than for a conventional configuration, it is important to incorporate a synchronism check relay as part of the synchronizing circuits. This is consistent with current Reclamation practice.

Protection System.—The protective relaying section of this document describes changes to the protective relaying scheme necessitated by high-voltage generation. This will necessitate changes to the lockout relay drawings and to plant wiring. Another potential impact may be to the generator CO_2 system: the high-voltage generator may not use CO_2 fire suppression, thus eliminating or changing the electrical and mechanical features of the system.

Metering, Instrumentation, and Alarm.—Elimination of the transformer and circuit breaker will reduce the amount of metering, instrumentation, and alarm functions into systems such as the control board, supervisory control and data acquisition (SCADA) system, event recorders, and temperature monitors. This will likely eliminate some wiring and transducers as well as create programming changes.

Auxiliary Power.—Stator cooling is required for high-voltage generators, which, in some plants, will be a new load (and control system) for auxiliary power and plant water systems. The elimination of the transformer and circuit breaker will decrease the ac and dc power demands by eliminating cooling system loads and breaker control system loads.

If an autotransformer is used, control and auxiliary power design and construction will be necessary.

Construction and Installation.—Modification to control and auxiliary power systems may best be performed by Reclamation staff (and PMA staff) rather than by a contractor, due to the complexity and sensitivity of the systems involved.

Operation.—Control and auxiliary systems will be significantly different with the implementation of high-voltage generation. Powerplant operations staff will need to be trained and existing documentation (e.g., Standing Operating Procedures) modified accordingly.

Maintenance.—New protective relays will require maintenance and testing. Maintenance staff will need to be trained and equipped.

Safety.—Provided that O&M staff are properly trained, there should be no additional safety issues regarding the control and auxiliary power systems.

Environmental.—No issues.

Issues and Concerns.—None.

F.2.7. Grounding System

The purposes of grounding are to limit electrical and mechanical damage from ground faults, to enable ground fault detection, and to limit transient overvoltages. Grounding configurations for conventional hydrogenerators are well established and the benefits well understood. A high-voltage generator such as Alstom's Powerformer™ will require a drastic change in powerplant grounding practices that must be addressed.

Powerformer™ is operated with the neutral ungrounded. This raises concern over means of protection and detection: How will stator ground fault protection be provided and what will be the impact on the local transmission line protection?

Conventional Generation

In a typical Reclamation powerplant, the generator is isolated from power system ground faults by the two-winding, generator step-up transformer. This transformer is delta connected on the generator side and grounded wye on the power system side. Through this configuration, the transformer becomes a source of ground fault current for the power system, while at the same time providing some degree of isolation for the generator. The transformer is important for determining the degree of sensitivity and level of selectivity for detection and protection from ground faults.

On the generator side of the transformer, protection from ground faults is needed, as well as a means to detect them. Since the transformer is delta connected on this side, neutral grounding is installed on the generator to provide a ground source. Since large fault currents would be harmful to the generator, high impedance grounding is used to provide just enough ground fault current for fault detection. To accomplish this, the generator windings are wye connected and the neutral is brought out and grounded through a high impedance. A stator ground relay detects any fault current passing through the impedance. This technique provides sensitivity and selectivity for ground fault detection, while minimizing the risk of iron burning within the generator. This stator ground protection is armed whether the unit is on or off line.

High-Voltage Generation

Powerformer™ generally does not require a step-up transformer; this results in the loss of a ground source for the power system. Also, Alstom's preferred method of installation is to leave the Powerformer™ neutral ungrounded. The purpose of this is threefold:

- To avoid injecting third harmonic voltages produced by the Powerformer™ into the power system
- To limit the magnitude of external line-to-ground faults to less than external three-phase fault levels
- To limit the level of machine damage caused by an internal fault

With the step-up transformer removed, another power system ground must be provided to help limit transient overvoltages and to allow for ground fault detection. In some powerplants, other system grounds are available locally. In the case of Folsom, the other unit step-up transformers and an autotransformer will serve the purpose. In cases where no other existing ground is available, a grounding transformer must be installed on the power system for this purpose.

Leaving the neutral ungrounded affects the ability to detect stator ground faults. Detecting Powerformer™ stator ground faults requires a different technique from the conventional configuration. Prior to synchronization, the Powerformer™ is isolated from the system. During this time, a grounded wye broken delta transformer provides ground fault detection for all but the last 20 percent of the stator winding near the neutral. To provide protection for this last section, current transformers are inserted within the winding at a distance equal to 20 percent of the winding from the neutral, and this portion of the stator winding is protected from ground faults by third harmonic current relays.

Design, Construction, and Installation.—The existing plant grounding configuration must be evaluated to determine the proper grounding arrangement for transient voltage protection and ground fault protection. Should the installation of a grounding transformer be necessary, a suitable location must be found.

Safety and Environmental.—There are no safety and environmental concerns related to properly designed and installed high-voltage generator grounding.

Issues and Concerns.—If a grounding transformer must be added, it will affect the cost of the high-voltage generation alternative.

F.2.8. Station Service Power Supply

In many plants, the existing station service power supply is derived from a step-down transformer connected to the generator medium-voltage bus. Since the medium-voltage is eliminated with a high-voltage generator retrofit applications, an alternate source for station service power is needed. Either a new, high-voltage station service transformer would be required or the existing station service transformer would be tapped from another generating unit. Although it is conceivable to derive the station service power from an auxiliary winding of the high-voltage generator (similar to the excitation supply), this is probably not practical in many cases, because this source would only be available when the unit is operating.

Modifications Required for Conversion from Conventional to High-Voltage Generation

Construction and Installation.—If implementing high-voltage generation requires a new, high-voltage station-service transformer, then auxiliary systems necessary for such a transformer (e.g., insulating oil storage, processing, and containment systems; deluge systems, and transformer cooling water) may be required. Tapping the existing station service transformer from another unit requires bus modification as well as control and protection changes. In the case of Folsom, station service power is supplied from the 115-kV switchyard via a stepdown transformer and from the tertiary winding of the 230–115-kV autotransformer.

Operation and Maintenance.—All operation and maintenance activities associated with station service transformers are still required. Transformer testing is needed, as well as spare parts.

Safety.—Safety risks are similar to those already in existence for station service transformers.

Environmental.—Should the station service transformer be replaced with a high-voltage, oil-filled transformer, environmental risks would increase to partially offset gains from eliminating the generator step-up transformer.

Issues and Concerns.—Station service power supply changes could increase the cost of the high-voltage generator option.

G. Impacts of High-Voltage Generator Installation

G.1. Equipment Impact Summary

Application of high-voltage generation at an existing installation will obviously have significant impact on plant equipment:

- Removal and replacement of existing stator winding and core
- Significant modifications to generator frame and air housing
- Replacement of the excitation system*
- Removal of the generator step-up transformer
- Removal of medium-voltage switchgear and buswork
- Installation of high-voltage potential transformers
- Replacement of generator protective relaying*
- Installation of high-voltage surge suppression
- Modification of unit control and auxiliary power systems
- Modification or replacement of high-voltage circuit breaker
- Modification to station service power supply system

Construction and installation will cause significant disruption of plant activities and affect work accomplished by O&M forces. However, conventional rehabilitation has similar impacts.

G.2. Operation and Maintenance Impact Summary

General operation of a high-voltage generator, including starting, stopping, and synchronizing will be very similar to a conventional unit. In cases where rotor size is increased, there may be minor differences in starting and stopping time.

Loading ramp rates may actually be better with high-voltage generators like Powerformer™ since heating effects on cable windings are less than on conventional bar windings. Likewise, overloading should be at least as feasible. This is due to the fact that with the higher voltage comes less current, resulting in less heating and reduced concern over thermal expansion of generator components.

Maintenance will be reduced and reliability increased due to elimination of the medium-voltage circuit breaker and step-up transformer. Some maintenance practices will change to accommodate high-voltage equipment. Drawings and O&M documents, such as Standard Operating Procedures, MAXIMO Job Plans, test procedures, and instruction books, will be affected as well.

* May also be required in the conventional rehabilitation alternative

G.3. Power System Stability Impact Summary

Of primary concern while initiating this research was how high-voltage generators, specifically Powerformer™, would perform in comparison to a conventional generator. Would it respond the same to system disturbances? Would overall system stability be improved or worsened? Would it supply more or less real power (watts) and reactive power (VARs)?

Questions regarding the impact of Powerformer™ on system stability can best be understood through a comparison of high-voltage generation characteristics with the characteristics of a conventional generator. Transient response, system damping, and VAR/voltage support all depend on machine design. From discussions with Alstom and the available literature, it was concluded that the reactance values of Powerformer™ are similar to values typical for conventional machines. In some cases, reactance values of Powerformer™ will correspond to the sum of those for a conventional machine and a step-up transformer. Therefore, it is expected that Powerformer™ can provide system support similar to that of the conventional generator configuration, considering the following:

- The conventional generator and Powerformer™ both control voltage at the machine terminals. The conventional generator controls the voltage at the low side of the step-up transformer while Powerformer™ controls the voltage of the high-side bus. At first glance, Powerformer™ would appear to be superior at regulating system voltage. However, it is likely that some degree of negative reactive current compensation, or "voltage droop," would be necessary to stabilize the voltage regulator of the Powerformer™ to the high-voltage bus. This issue is even more important if more than one Powerformers™ is connected in parallel. The net result would be a Powerformer™ voltage-regulating characteristic similar to that of a conventional generator with line drop compensation added to compensate for some of the impedance of the step-up transformer.

- It has been noted that the net WR^2 (rotating inertia) of Powerformer™ may be 20 percent larger than that of a conventional machine, due to the larger rotor. A larger inertia will slightly increase the transient (first swing) stability. On the other hand, increasing the inertia of the machine also slightly decreases the damping of the generator torque control loop. Both transient and post-transient stability, however, depend much more on the excitation control system, which would mask most of the effects of the inertia difference.

Alstom has demonstrated that the required upper limit of the operating range of an excitation system for Powerformer™ is less than the upper limit required for a conventional design. If a Powerformer™ is designed with lower transient and subtransient reactance values than would be achievable with a conventional design, it is then possible to provide more VAR support and improve system stability. The trade-off for the increased performance would be an increase in the available fault current.

It is recommended that system stability studies be performed prior to specification of machine design characteristics and during installation/testing. This is true for both a conventional design and a high-voltage generator.

Implementing a high-voltage generator, like any major equipment change at Reclamation powerplants, could have significant impacts, both positive and negative, on the power system. The power marketing administrations must be involved in assessing the system impacts locally. Consultation with PMAs from the early stages of study and design is essential.

G.4. Safety Impact Summary

Application of high-voltage generation will have impact on powerplant safety. Included are:

- Electric fields in the powerplant due to higher voltages do not appear to provide any increased safety risk. Magnetic fields should be reduced due to less current.

- Elimination of the oil-filled, step-up transformer will reduce safety risks from explosion, fire, oil, and smoke contamination.

- Elimination of the medium-voltage switchgear will reduce the safety risk associated with maintaining this equipment and possible explosion in the plant from a faulty breaker. In the case of SF_6 breakers, retirement will eliminate the risk of release of toxic SF_6 byproducts.

- Replacement of medium-voltage instrument transformers with high-voltage ones will not inherently improve safety, but newer equipment with less wear and tear that meets modern safety codes is always a safety plus.

On balance, application of high-voltage generation should reduce the total safety risks of plant operation and maintenance from those found in conventional generation.

G.5. Environmental Impact Summary

Application of high-voltage generation will change the risk of environmental impacts. Included are:

- Elimination of the oil-filled, step-up transformer will reduce or eliminate environmental risks from oil spill either during maintenance or as a result of tank or bushing rupture. Likewise, air pollution from burning oil would be avoided.

- Potential installation of an oil-filled station service transformer or an autotransformer would reduce some environmental gains from elimination of the generator step-up transformer.

- In the case of SF_6 medium-voltage circuit breakers, retirement will eliminate the risk of SF_6 (a potent “greenhouse” gas) escaping into the atmosphere.

- Replacing medium-voltage instrument transformers will eliminate insulating oil in some cases, but addition of high-voltage instrument transformers will likely require additional oil and its associated environmental risk.

- Longer machine life reduces environmental impact by reducing manufacturing and disposal effects.

On balance, application of high-voltage generation should reduce the total environmental risks from those found in conventional configurations.

H. Economic Evaluation

An important question is whether high-voltage generation at Reclamation powerplants is justified economically. To answer this, it is important that all costs be considered over the expected life of the machine—a life cycle cost analysis and comparison must be performed.

It is also important to compare viable technical alternatives for generator rehabilitation. It is justified to consider the alternative of continuing operation and maintenance as it is currently conducted —this would be a “baseline” alternative. It is certainly important to compare the costs of high-voltage generation with conventional generator rewind and transformer replacement.

As the technical discussion above implies, application of high-voltage generation eliminates or reduces significant life-cycle capital expenditure and maintenance cost, due to the elimination of some major equipment. On the other hand, it requires significant plant modification and extra equipment costs that must be accounted for. Generically, categories that may be considered in the economic evaluation for the different options include:

Item	**Conventional**	**High-Voltage**
Generator stator core or winding modification	YES	YES
Generator rotor/field modification	NO	LIKELY
Generator structure modification	NO	LIKELY
Generator maintenance required	YES	YES
Excitation system replacement	LIKELY	LIKELY
Transformer replacement/removal	IF OLD	REMOVAL
Transformer maintenance required	YES	NO
MV circuit breaker repl./remove	IF OLD	REMOVAL
MV circuit breaker maintenance required	YES	NO
HV circuit breaker replacement	NO	MAYBE
HV circuit breaker maintenance required	YES	YES
Buswork modification	NO	YES
Instrument transformer installation	NO	YES
Surge arrester installation	NO	YES
Grounding transformer installation	NO	MAYBE
Autotransformer installation	NO	MAYBE
Protective relay modifications	NO	YES
Control/instrumentation mods	IF OLD	YES
Auxiliary power modifications	NO	YES
Transformer oil spill cleanup	YES	NO

A complete cost comparison would:

- Include costs associated with lost opportunity generation due to outages from generator winding, transformer, or circuit breaker failure. This is a risk-based analysis.

- Include costs of lost opportunity generation due to construction outages required by each option

- Include potential value of ancillary services provided by each option

- Incorporate increased efficiency of equipment available for each option

- Incorporate increased reliability and availability made possible by elimination of failure risk and maintenance/testing of medium-voltage equipment

- Include increased output made available by technical improvements

- Incorporate savings from reduced capital investment

- Use the same life cycle periods for all alternatives
- Compare life expectancy of all alternatives
- Be expressed in present worth terms
- Use a consistent interest rate such as the Federal Discount Rate
- Compare costs and benefits on a consistent basis, such as annually
- Include costs of maintenance required by each option

A risk analysis tool based on equipment failure probability is being developed under the Reclamation Powerplant Life Extension research project. This tool will quantify these risks in dollar terms and may be used in performing the high-voltage generation economic analysis. Of course, some risks apply to both high-voltage generation and conventional installations, while other risks are specific to the technology applied. Avoidance of these risks should be considered as a benefit to offset costs.

Elimination of the step-up transformer in the high-voltage option would seem to increase overall efficiency of the unit, since transformer losses would be eliminated. While transformer losses are indeed eliminated, modern transformers are much more efficient than older transformers, so losses of newly installed transformers would be less than current losses. Therefore, the overall efficiency of the high-voltage unit is only slightly higher than a conventional configuration, and the total economic analysis is not much affected by the transformer efficiency differences. However, the elimination of the transformer does have positive impact on the analysis in other areas, such as capital equipment costs. The efficiency improvement and economics of each application of high-voltage generation must be evaluated individually to determine the best option in comparison to conventional rehabilitation.

Turbine replacement and other improvements not integral to the application of high-voltage installation should be included in both the conventional and high-voltage cost calculations or segregated so that costs can be compared fairly.

I. Applications

I.1. High-Voltage Generation at New Powerplants

Although most potential applications of high-voltage generation at Reclamation powerplants in the near term are for retrofit, use of this technology should be considered for any new facilities as well. Complications resulting from rehabilitating existing equipment would be nonexistent, and the return on investment for new facilities should be much higher than for retrofit installation, since expensive modifications would not be necessary with a plant designed and constructed from the outset for high-voltage generation.

I.2. Potential Existing Reclamation High-Voltage Generation Sites

Some Reclamation powerplants, listed in table 3, are more likely candidates than others for high-voltage generation application. The criteria for preliminary screening are:

- MVA and voltage rating compatible with current state of high-voltage generation capability.

- Age of generator winding approaching (85%) of typical reliable life span. This is approximately 25 years. Typical reliable life span is 30 years, when probability of winding failure having occurred exceeds 20 percent (based on Weibull Distribution of failures of several hundred hydrogenerators as compiled by the U.S. Corps of Engineers).

Table 3.—Potential High-Voltage Generation Sites

Plant Name	Line Voltage (kV)	MVA	Winding Age (Yr)
Big Thompson	13.8	4.5	43
Boysen	115 & 34.5	8.3	50
Canyon Ferry	115	16.7	48
Chandler	115	6.3	46
Deer Creek	44	2.75	44
Estes	115	16.7	52
Folsom	115 & 230	69	33
Fontenelle	69	11	34
Kortes	115	13.3	19
Mary’s Lake	115	9	51
Minidoka 7	34.5	6	30
O’Neill	69	4.2	34
Parker	161	30	60

Other generating units may be candidates as well, based on age and condition. Each unit must be evaluated individually. Alstom Power is currently developing higher voltage Powerformers™; 230 kV may be possible in the near future.

A high-voltage generation pilot project at a Reclamation facility would be very beneficial for validating the findings of this report, for evaluating the effectiveness of this technology, and for assessing the applicability at other Reclamation powerplants.

I.3. Case Study—Folsom Powerplant Unit 1

To clearly identify and address the issues related to retrofitting an existing Reclamation hydrogenerator with high-voltage generation, Folsom Powerplant Unit 1 was chosen as a case study. The technical details of this case study are included in appendix A . The economic details are included in appendix B. Folsom Unit 1 is a good choice for a variety of reasons:

- Ratings for this unit are typical for Reclamation machines and these ratings are within the capabilities of Powerformer™.
- The age and condition of the generator and step-up transformer are appropriate for consideration. Rehabilitation, either in conventional fashion or with high-voltage generation, is imminent.
- The busing arrangement is ideal, since the generator has its own high-voltage breaker.
- Reclamation owns and operates the high-voltage breaker. This makes control and protection modifications easier.
- An existing autotransformer and other generating units can provide a point of power system grounding. This simplifies the grounding design and is less expensive.
- The powerplant structure will accommodate Powerformer™ construction and installation. Crane lift and construction space are adequate.
- A key power customer, SMUD, is interested in possible application of high-voltage generation at Folsom. This is important from a funding perspective.
- The site O&M staff are very interested in reducing maintenance, increasing efficiency, and improving reliability.

Preliminary design concepts have been developed as part of this case study. Appendix A includes drawings, relay recommendations, and major component discussions for Unit 1.

Implementation of high-voltage generation at Folsom is an Area Office decision outside the scope of this report. However, this report could provide justification for that decision at Folsom or at other Reclamation locations.

The economic study for Folsom Unit 1 shows that the life cycle cost of Powerformer™ retrofit based on a 50-year life cycle could save about 35 percent over the cost of the conventional rehabilitation. The overall operating efficiency is expected to increase by approximately 1 percent. Additional and valuable ancillary services are also available with the Powerformer™ option.

I.4. Power Customer Application Issues

Managers who are considering the possibility of installing high-voltage generation at their facilities must work in close cooperation with the power customers that benefit from the power produced at Reclamation's powerplants. Such customers have a keen interest in increasing the efficiency, reliability, and safety of the power generation facilities, while minimizing the operation and maintenance costs. This should be handled in the same manner as any major change, replacement, or new addition to Reclamation's power facilities. Because the power customers ultimately finance the majority of the capital improvements, as well as the annual O&M costs, through the power rates and/or through advance funding programs, it is important to consider the power customers' input. The best practice is to involve power customers from the beginning in every step of the process. Since high-voltage generation is a relatively new technology, both Reclamation management and power customers must be fully cognizant of the risks and rewards.

If high-voltage generation technology continues to show technical and economic advantages, as has been indicated in this research, comparison between the alternatives of rehabilitating the generating unit conventionally or retrofitting using high-voltage generation will need to be made before proceeding with either alternative. Reclamation and customers alike want the best alternative. A careful comparison will be needed to ensure the best technical and economic decision.

Reliability is of paramount importance to most power customers. Reliability of conventional windings is well understood and thoroughly documented. Insufficient operating experience exists to verify that high-voltage windings will be more or less reliable over the expected life, but early operating experience and accelerated life tests are encouraging. A certain amount of risk accompanies changing technology but so do potential benefits. With the elimination of the medium-voltage switchgear and step-up transformer, it is reasonable to assert that reliability and availability will be improved by eliminating the potential for failure and the need for maintenance and testing outages for these components.

Costs and Benefits.—The costs that are ultimately funded, and the benefits that are reaped by Reclamation power projects, are another important point to consider. When comparing costs and benefits, the entire life cycle of the generating unit should be considered. Significant capital costs are to be expected for either conventional or high-voltage alternatives. However, high-voltage generation is likely to be more capital intensive initially. On the other hand, future capital for replacing transformers and medium-voltage circuit breakers will not be required. O&M costs will likely be less with high-voltage generation, due to the elimination of major components in the power-generation train. Efficiency may be increased, due to fewer losses. When taken all together and considered over a complete life cycle, high-voltage generation may prove much more attractive.

Environmental risks and benefits are often important to power customers. Power customers interested in reducing potential environmental cleanup costs may find high-voltage generation very attractive.

I.5. Sacramento Municipal Utility District Applications

Sacramento Municipal Utility District (SMUD) has "shadowed" this Reclamation research effort and provided much important technical support. SMUD, as a key power customer, will play a significant part in any decision to install a high-voltage generator or conduct a conventional rehabilitation at Folsom Powerplant.

In addition, SMUD is considering high-voltage generation at its own hydroelectric powerplants. Among those being considered are Loon Lake, a single-unit plant, and Iowa Hill, a pump-storage facility under study, both located in the Sierra Nevada Mountains east of Sacramento, California.

For more information regarding SMUD's plans for high-voltage generation, please contact Mr. Ed Roman at eroman@smud.org or Mr. John Wetmore at jwetmor@smud.org.

J. Conclusions and Recommendations

Conclusions reached in this research are:

- High-voltage-generation technology is viable as an alternative to conventional (medium-voltage) hydrogeneration methods.
- High-voltage generation is suitable at some Reclamation facilities depending on line voltage, machine rating, and plant configuration.
- High-voltage generation is likely more reliable and has longer life expectancy than conventional generation.

- High-voltage generation is not simple to retrofit into existing powerplants. Significant changes would be needed in plant equipment and systems as well as to some maintenance practices.

- High-voltage generation can meet plant and system operational needs.

- Safety and environmental risks can be reduced with high-voltage generation through elimination of the step-up transformer and medium-voltage circuit breaker.

- Preventive maintenance can be reduced with the elimination of equipment. Likewise, maintenance costs should decrease with high-voltage generation.

- High-voltage generation may be a cost-effective alternative to conventional unit rehabilitation when considered on a life cycle benefit-to-cost basis.

- Technical and economic viability (feasibility studies) will need to take place on a site-specific basis.

- Close cooperation between prospective Reclamation users and the local Power Marketing Administration as well as Preference Power Customers is essential to success.

RECOMMENDATIONS

Reclamation power managers should consider high-voltage generation case by case.

A pilot project should be developed to evaluate the effectiveness and future applicability of high-voltage generation at other Reclamation facilities.

Appendix A
Case Study—Preliminary Design for Folsom Powerplant

Throughout the course the High-Voltage Generation Research, Folsom Powerplant generating Unit No.1 was used as a case study to evaluate design, construction, installation, O&M, and economic issues. This unit and the associated step-up transformer and medium-voltage circuit breaker are approaching the end of their expected lives—some form of rehabilitation/replacement will take place in the near future. Folsom management supported the idea of investigating high-voltage generation as an option in the rehabilitation scheme.

Alstom Power investigated Folsom Unit 1 for Powerformer™ application. The following table compares current ratings and potential Powerformer™ ratings:

Folsom Unit 1		
Item	**Present**	**Powerformer™**
Generation voltage	13.2 kV	115 kV
Power system voltage	115 kV	115 kV
Capacity	70 MVA	70 MVA—Some uprate may be possible
Power factor	0.90	As needed—possibly 0.90
Speed	163.6 rpm	163.6 rpm
Excitation system	Rotating	Rotating brushless or static
Generator winding	Conventional winding: age 28 years	XLPE cable-type
Step-up transformer	Age 45 years	Not applicable
Unit (MV) circuit breaker	Age	Not applicable
Turbine	Age 45 years	Not replaced for Powerformer™

Single-Line Diagram

This appendix includes a preliminary main single-line diagram and other drawings showing application of a Powerformer™ for Unit 1. The following discussion supplements these drawings in describing the Powerformer™ application.

Generator Stator and Rotor Components

For the conventional rehabilitation option, the generator stator winding would be replaced. It is likely that the core and bearings would require little or no modification. The cooling system would probably be reused. Likewise, the rotor and field winding would likely be reused. The existing rotating exciter would be replaced with a static exciter and digital voltage regulator.

In the Powerformer™ option, the stator winding and core would be completely replaced. Bearings may require replacement. The rotor (poles and rim) and field winding would likely be replaced and probably the rotor spider. The cooling system would be completely replaced to reflect the cooling water needed for the Powerformer™. The exciter would be replaced with a brushless or solid-state exciter.

Generator Step-Up Transformer and Medium-Voltage Unit Breaker

For the conventional rehabilitation option, the step-up transformer and medium-voltage unit breaker would be replaced in kind. In the Powerformer™ option, these items would be eliminated entirely.

High-Voltage Circuit Breaker

For the conventional rehabilitation option, there will be no modifications required to the high-voltage breaker. In the Powerformer™ option, it will be possible to use the existing high-voltage breaker. In this case, the high-voltage breaker is specifically for Unit 1, and it is operated and maintained by Reclamation.

Buswork and Surge Arresters

For the conventional rehabilitation option, no modifications are expected for the medium-voltage surge arresters and buswork.

In the Powerformer™ option, it will be necessary to remove existing medium-voltage surge arresters and install high-voltage surge arresters to protect the Powerformer™ winding. Medium-voltage buswork will be removed and replaced with high-voltage buswork.

Instrument Transformers

The following instrument transformers will be required for high-voltage generation:

- Current transformers (nine sets of three, and one single)
  - Two sets of multi-ratio current transformers (CTs) will be required in the 115-kV switchyard to supply total redundancy; however, there is only one set of CTs located on the bus side of breaker JV1M. Therefore, the addition of a new set of free standing 115-kV CTs will be necessary in the 115-kV switchyard.
  - Five sets of multi-ratio current transformers will be required in the powerplant in conjunction with the Powerformer™. These CTs will be installed over the Powerformer™ cable system and, so they will be low voltage class. One set of CTs must be revenue class.
  - One set of single-ratio current transformers will be required to be installed within the Powerformer™ by Alstom. This set of CTs is to be located 20 percent of the distance from the neutral, to provide stator ground fault protection. (Alstom is developing a new method of 100% stator ground fault protection using phase and neutral CTs in lieu of those located in the Powerformer™.)
  - One multi-ratio current transformer will be required to be installed in the neutral in series with the arrester. This CT will supply an overcurrent relay for the purpose of recording an arrester discharge.
  - One set of current transformers for the excitation system.
- Potential transformers (two sets of three)
  - One three-phase set of 115-kV potential transformers with dual secondaries located near the Powerformer™. One secondary is for a grounded wye broken delta connection for ground fault protection. The other secondary is for relaying, metering, synchronizing, and regulator sensing.
  - One three-phase set of 115-kV potential transformers with dual secondaries located on the bus side of the 115-kV unit breaker JV1M. Secondaries are for redundant sets of distance relays.

Protective Relaying

The following protective relaying will be required for high-voltage generation:

- 11LP/11LB (primary and redundant backup microprocessor-based distance/overcurrent protection packaged relays). These elements are available in an SEL 311C and provide the following protection from the 115-kV switchyard looking toward the generator:

    - No. 21.—Relay element provides distance element looking toward the generator, providing phase and ground fault protection for generator, and from the generator to the switchyard cable.

    - No. 67G.—Relay element provides backup directional ground fault protection looking toward the generator. The protection backs up the 11GP and 11GB ground fault protection elements.

    - No. 50/51N.—Relay element provides backup directional phase overcurrent protection. The protection backs up 11GP and 11GB phase overcurrent protection.

- 11GP and 11GB (primary and redundant backup microprocessor-based generator protection packaged relays). The following elements are available in an SEL 300G for primary protection and a Beckwith 3425 for redundant backup protection:

    - No. 24 (overexcitation-volts/Hz).—Provides generator overexcitation protection using volts/Hz inverse time, instantaneous, and alarm elements.

    - No. 40 (loss-of-field).—Prevents generator from operating when field current is absent or of insufficient magnitude as to cause generator to operate beyond its stator heating capability limit curve, or to slip poles.

    - No. 46 (negative phase sequence).—Trips generator when generator stator phase percent current unbalance exceeds a user-selected inverse time current unbalance condition.

    - No. 50BF (breaker failure); Trips backup power circuit breakers when the generator unit breaker fails to trip under load or under fault conditions.

    - No. 59I (instantaneous overvoltage).—Trips generator unit when generator stator voltage instantaneously exceeds a preset magnitude.

  - N No. 59T (timed overvoltage).—Trips generator unit when generator stator voltage exceeds a user-selectable inverse time overvoltage curve or exceeds a preset voltage magnitude for a definite preset time period.

  - N No. 78 (out-of-step).—Prevents the generator from operating after slipping a pole. Provides some degree of backup for the loss-of-field relay element.

  - N No. 81 (overfrequency).—Trips generator if generator stator frequency exceeds a preset instantaneous and definite time overfrequency setpoint. Provides backup to the generator governor instantaneous and sustained overspeed switch.

  - N No. 87G (generator differential).—Provides generator stator differential current phase and ground fault protection.

  - N No. 21 distance relay.—Provides generator directional distance relaying protection from generator neutral toward switchyard. Provides generator fault protection and switchyard backup fault protection.

  - N No. 50/51N (timed/instantaneous ground overcurrent).—Provides generator ground fault protection after the generator has been synchronized to the power system.

- No. 59G* overvoltage relay.—Used in a broken delta potential-transformer-configured circuit to detect generator stator ground faults when the generator is energized but not synchronized to the power system.

- No. 51TH* third harmonic overcurrent relay.—Used to detect a stator ground fault in the 20 percent of the stator winding nearest the neutral by detecting the presence of third harmonic currents during stator ground faults. NOTE: In generators with high impedance grounded neutrals, this protection is usually provided by detecting the absence of third harmonic voltages in the high impedance neutral grounding transformer secondary circuit. However, since high impedance generator grounding is not recommended by the Powerformer™ manufacturer, the 51TH overcurrent detection relay or some other method must be used.

- No. 49 RTD (resistance temperature detector) relay.—Used to detect overheating in the generator stator windings

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* The 11GP/11GB No. 64G (stator ground) element can be used to provide redundant protection for element Nos. 59G and 51TH, if so desired.

- No. 50N.—Instantaneous overcurrent relay used to record an alarm for a generator neutral arrester discharge. This relay element function could be furnished by the 11GP/11GB relays.

Grounding

The following must be considered for grounding with high-voltage generation:

- *Normal Situations.*—If no ground sources existed at Folsom, it would be necessary to install a grounding transformer to supply a ground path for relaying purposes and a power system ground reference. But Folsom does have two unit step-up transformers, one autotransformer, and a very stiff tie line to Roseville. For all reasonable operating situations, Folsom Powerplant does not need any additional ground sources to enable ground fault detection or to provide a power system ground reference.

- *Special Situations.*—Prior to synchronization, the Powerformer™ is isolated from the system. During this time, a grounded-wye, broken-delta potential transformer provides ground fault protection for approximately 80 to 90 percent of the stator winding via device 59G. In order to provide protection for the remainder of the winding near the neutral, the third harmonic current should be measured with a set of CTs inside the Powerformer™.

Control, Protection, and Auxiliary Power Systems

The conventional rehabilitation option will require no significant modifications to the control, protection, metering, indication, alarm, or auxiliary power systems.

The Powerformer™ option will have a significant impact on these systems. Some of these are:

- Elimination of all step-up transformer indication, alarm, and protection functions

- Elimination of all medium-voltage circuit breaker control, indication, metering, and protection functions

- Redesign and reconstruction of the generator indication, alarm, and auxiliary power functions

- Redesign and reconstruction of the high-voltage circuit breaker control and protection functions, including synchronizing

- Redesign and reconstruction of the instrument transformer secondary circuitry

For purposes of the Folsom study, it is assumed that redesign and reconstruction of the protective relaying schemes and exciter control and protection is similar for both conventional and Powerformer™, since most likely, these systems will be completely replaced in either option.

Economics

A benefit/cost study was conducted for a conventional rehabilitation of Folsom Unit 1 to Powerformer™ retrofit. A life cycle of 50 years was used for each case. The economic study included capital investment costs of generator, transformer, and circuit breaker, including the time value of money; changes in efficiency; the cost of operation and maintenance; cost of environmental risks; value of energy; and replacement power cost. Equipment and plant modifications considered in the study include all those described above in this appendix.

The economic study shows that the life cycle cost of a Powerformer™ retrofit could be approximately 136 percent of the cost of the conventional rehabilitation and still achieve parity. See appendix B for details.

Drawings

The attached drawings show the preliminary design for Folsom Unit 1.

485-ECD-1000	Folsom Powerplant With Powerformer™—Switching Diagram (May 11, 2001)
485-ECD-1001	Folsom Powerplant With Powerformer™—Single Line Diagram (May 15, 2001)
485-ECD-1002	Folsom Powerplant With Powerformer™—Relay and Device Function Sheet (May 17, 2001)

Appendix B

Case Study—Economic Analysis for Folsom Powerplant

Summary

The analysis for this case study resulted in obtaining “break-even” multiples of the avoided costs of several conventional generator rehabilitation scenarios, where a generator with varying equipment life was compared to a Powerformer™ installation. These multiples are considered to be the highest allowable cost of the Powerformer™ installation when compared to the base cost of each conventional generator rehabilitation. This base cost will vary between scenarios. To calculate these multiples, a lifecycle cost estimate was first calculated for each of the conventional generator scenarios over the expected 50-year lifecycle of the Powerformer™. Any additional unique lifecycle costs and benefits attributed to the Powerformer™ were then respectively subtracted or added to the each of the conventional generator rehabilitation lifecycle costs. These modified lifecycle costs were then respectively divided by their unmodified lifecycle costs to arrive at the “break-even” multiples.

The lifecycle costs took into account the service life of the components and the replacement and O&M costs for each conventional generator rehabilitation scenario. With this method, estimates for procurement and installation costs of the Powerformer™ are not required, and the decision to choose the Powerformer™ is basically determined by how close the total quoted installed Powerformer™ cost comes to the total estimated modified lifecycle costs. It must be noted that these “break-even” multiples cannot be compared against each other on an absolute basis, where the highest multiple would indicate the best scenario to pursue. Instead, a conventional generator replacement scenario has to be independently chosen first. From this choice, a comparison can then be made between the conventional generator rehabilitation scenario and the Powerformer™ scenario using the corresponding “break-even” multiple.

Conclusion

Based on the review of the break-even multiples and an estimate of the cost to furnish and install the Powerformer™ at the selected test site, the Powerformer™ was found to provide an economic advantage in all but one case. That case appears to be a site condition issue and may be mitigated by future advancements of the Powerformer™ design.

The degree of the economic advantage was found to be a function of the fuel escalation rate for natural gas. The economic viability was present through all values of escalation over the life cycle of the winding of the Powerformer™.

Approach

The estimated allowable cost of the Powerformer™ was analyzed from the perspective of the avoided cost associated with the replacement of the major components of a conventional generator. The lifecycle costs of each main component were evaluated, including the main generator components, such as the core, winding, field winding, excitation system, and the step-up transformer.

Following initiation of the analysis, an argument was raised that the cost of a Powerformer™ would necessarily include development costs, and a pure cost estimate would require the manufacturer to determine how much of the reasearch and development costs would be included in this first U.S. installation. In order to remove these concerns from consideration, a "bottom line" approach was used. That is, what is the ultimate cost of a Powerformer™ that a customer would consider funding that still retains a cost advantage over a conventional generator replacement? The analysis examined the total Powerformer™ directly against a conventional generator on a pure lifecycle cost perspective, which included the benefits of using the Powerformer™. The benefits would be in the form of the costs avoided by replacing the conventional generator with a Powerformer™.

As discussed previously in this report, the principal difference between the conventional generator application and Powerformer™ is that a Powerformer™ winding lasts longer and does not require a main step-up transformer and a unit medium-voltage circuit breaker. Installation of the Powerformer ™ will require some components of the existing generator to be replaced in order to accommodate the particular design of the Powerformer™. The design differences that allow the Powerformer to produce power at higher voltages also allow for reduced losses, as demonstrated in the Folsom application. Generator components that are generally replaced for a Powerformer™ include the stator frame, core, pole pieces, field winding, and excitation system. In the analysis, it was assumed that the excitation system would be replaced as part of a conventional rewind. For one of the scenarios, the core was also assumed to be at the end of its service life and would also be replaced.

The main component in a conventional generator that creates the most work is the main stator winding. The stator winding for medium-voltage generators lasts about 25 to 30 years. Normally, the core of a generator will last 50 years. The main step-up transformer will last 40 years. In order to complete an accurate assessment of the Powerformer, the benefits attributed to a Powerformer™ must be combined into the "break-even" multiplier of a conventional generator replacement. These benefits include reduced losses brought about by the elimination of the step-up transformer, reduced O&M of the transformer, and avoided loss of power revenues during the extended outage period for the conventional generator rewind.

Looking at the avoided costs over a 50-year period, a Powerformer™ installation would avoid one generator rewind and one transformer replacement. That is, in a conventional unit, both the core and winding are replaced at the same time that a Powerformer™ would be installed. The conventional unit would then require a winding replacement, while the Powerformer™ would not require such a refit outage. If the transformer is not at its full service life, then the replacement is delayed. Since the transformer has 40 years of life remaining at the end of the analysis period, its cost is prorated at the second replacement. In one scenario, a smaller step-up transformer is installed as part of the Powerformer™ installation, thus the avoided cost is the difference between a full size transformer replacement and a smaller intermediate transformer.

Site Application

Folsom Powerplant was used as the working example for the Powerformer™ application. For the replacement unit under consideration, the generator winding, core, and step-up transformer, have reached their full service life. The analysis was performed using current estimated costs for a conventional generator rewind and transformer replacement with all their associated costs. The future costs for the generator rewind and transformer replacement were maintained at the current dollar level. The future cost of power was escalated at an estimated fuel (natural gas) index escalation rate of 2.00 percent. All costs were brought back to Net Present Value using a discount rate of 5.50 percent. The operation and maintenance costs for the conventional generator were based upon the average 5-year costs for O&M at the Folsom powerplant. Efficiency analysis used preliminary Powerformer™ design data and the acceptance test data for the existing Folsom generator and transformer under analysis.

Revenue Stream and Efficiency

A factor that influences the “break-even” multiples is the lost power revenue of the generating unit during replacement work. The time to replace some component of a conventional unit may result in spilling water that is beyond the reduced capacity of the powerplant to accommodate. In addition, revenue may be lost in driving the remaining units in a powerplant out of a peaking mode of operation, thereby causing a lower revenue stream from power generated off-peak with attendant lower market prices.

Other factors that influence the “break-even” multiples include increased efficiency, or decreased efficiency in the case of a conventional design. The magnitude of the increased efficiency of a Powerformer™ over a conventional generator is determined by the ability of the Powerformer™ to completely avoid a step-up transformer from the unit to the outgoing bus. If an intermediate step-up transformer were needed for the Powerformer™ to reach full outgoing bus voltage, the efficiency gain would be somewhat reduced but not completely eroded. An auto-transformer can be used as the intermediate step-up transformer. They are usually associated with greater efficiency than a two-winding transformer, but their losses and additional cost decrease the benefits of the Powerformer™ application.

Analysis of powerplant operations revealed a high plant capacity factor that reduced lost power generation during the overhaul period due to spill in all but the most hydrologically wet years. Specifically, this was the hydrologic condition that has a 10 percent probability of being equaled or exceeded in any given year. Analysis showed that this defined wet condition results in high releases exceeding the capacity of the remaining 2 units at the Folsom Powerplant in only 2 months that were toward the latter part of the outage period. No attempt was made to quantify the impact loss of peaking capability due to the remaining units being base loaded.

For this analysis, a Powerformer™ was found to have somewhat lower losses than a conventional generator. The overall efficiency of the Powerformer™ application was further increased as compared to the overall efficiency of the conventional generator/transformer because of the elimination of the need for a step-up transformer. Losses were very dependent upon specific design considerations. The first round of design revealed a unit with armature and iron losses slightly higher than a conventional unit. Review of machine characteristics revealed some areas of improvement that resulted in lower armature and iron losses. The changes to the design imply that the Powerformer™ application may have some inherent design flexibility that can only be verified as the Powerformer™ is applied at other sites.

Summary of Site Application

The analysis of a Powerformer™ application at Folsom revealed that the Powerformer™ cost to furnish and install can exceed the cost of a conventional generator and step-up transformer by 1.0 to 1.5 and still be competitive with conventional. The primary benefit shown by the Powerformer™ was largely due to the potential lost power generation during the second conventional rewind performed at 25 years. The next benefit influencing the result was the unit disassembly and reassembly costs for the second rewind, followed by the increased efficiency of the Powerformer™. The latter was surprisingly found to be around 1.1 percent for pure Powerformer™ and 0.7 percent for a Powerformer™/autotransformer combination. The application of the Powerformer™ has other benefits that favor it. As an example, the step-up transformers are located on the upper powerplant deck; the presence of the a large quantity of mineral oil used in the transformer for cooling and insulation in close proximity to the tailrace is eliminated with application of a Powerformer™. However, this advantage is lost if an auto-transformer is needed to achieve the required line voltage.

In the Folsom application, there is no medium-voltage unit breaker. The unit breaker is on the high side of the transformer. The Powerformer™ economics, therefore, did not benefit from the avoided breaker replacement and associated maintenance.

The Powerformer™ was found also to allow for production of additional ancillary services. The benefits occurred during both the initial installation of the Powerformer™

and avoided second rewind. The additional ancillary services during the initial installation of the Powerformer™ were possible, as the conventional unit being replaced is able to remain on line during the initial construction phase of the Powerformer™. Instead of tearing the conventional unit down to replace the stator iron, major components of the Powerformer™ are assembled at the site while the conventional unit remains in operation. Up to 3 months of additional generation were possible prior to teardown. The time to complete the unit is also reduced, allowing for additional generation when a conventional unit would still be in reassembly. The additional ancillary service production during the avoided second rewind addresses the fact that a Powerformer™ would be available for generation, while a conventional unit would be undergoing the winding replacement. On all of theses conditions, the reservoir releases at Folsom were considered to be within the capacity of the remaining two units, and therefore no energy production was lost.

The following scenarios were evaluated:

1. Replacement in Year 1 of a conventional 13.8-kV, 71.7-MVA generator (which includes the stator core, stator winding, rotor, and 13.8- to 115-kV step-up transformer) with a 115-kV, 71.7-MVA Powerformer™. This provides the overall benefit of installing the Powerformer™.

2. Replacement in Year 1 of a conventional 13.8-kV, 71.7-MVA generator (which includes the stator winding, rotor, and a 13.8- to 115-kV step-up transformer) with a 115-kV, 71.7-MVA Powerformer™. The stator core was assumed to be functional and was replaced in Year 25. This analysis shows the sensitivity of the stator core replacement.

3. Replacement in Year 1 of a conventional 13.8-kV, 71.7-MVA generator (which includes the stator winding and a 13.8- to 115-kV step-up transformer) with a 115-kV, 71.7-MVA Powerformer™. The stator core and rotor winding were assumed to be functional and were replaced in Year 25. This analysis assesses the ability to perform a mid-life plant renovation with a Powerformer™.

4. Replacement in Year 1 of a conventional 13.8-kV, 71.7-MVA generator (which includes the stator core, stator winding, rotor, and a 13.8- to 115-kV step-up transformer) with a 115-kV, 71.7-MVA Powerformer™ and a 115-kV to 230-kV step-up auto-transformer. This analysis examines a more typical application of a Powerformer™, where the system voltage is 230 kV.

Scenario 1

The analysis indicates that the cost of the Powerformer™ must not exceed a 1.52 "break-even" multiple of the cost of a conventional generator and step-up transformer to provide a positive benefit-to-cost ratio. The "break-even" multiple drops to 1.36, if the second rewind does not occur in a wet year. The major factors in this scenario were the losses due to the step-up transformer and the disassembly and reassembly cost of the generator for the second (Year 25) conventional winding replacement. Multiples varied with fuel escalation from 1.25 at -1.0 percent fuel escalation to 1.60 for +5 percent fuel escalation. No escalation sensitivity analysis was performed for a wet year.

Scenario 2

The analysis indicates that the cost of the Powerformer™ must not exceed a 1.57 "break-even" multiple of the cost of a conventional generator and step-up transformer to provide a positive benefit-to-cost ratio. The "break-even" multiple drops to 1.39, if the second rewind does not occur in a wet year. The major factors in this scenario were the losses due to the step-up transformer and the disassembly and reassembly cost of the generator for the second (Year 25) conventional winding replacement. The higher multiple is due in part to the lower cost of a conventional machine without an initial stator core replacement. Multiples varied with fuel escalation from 1.27 at -1.0 percent fuel escalation to 1.66 for +5 percent fuel escalation. No escalation sensitivity analysis was performed for a wet year.

Scenario 3

The analysis indicates that the cost of the Powerformer™ cannot exceed a 1.60 "break-even" multiple of the cost of a conventional generator and transformer to provide a positive benefit-to-cost ratio. The "break-even" multiple drops to 1.41, if the second rewind does not occur in a wet year. The major factors in this scenario were the losses due to the step-up transformer and the disassembly and reassembly cost of the generator for the second (Year 25) conventional winding replacement. The higher multiple is due in part to the lower cost of a conventional machine without an initial stator core and rotor winding replacement. Multiples varied with fuel escalation from 1.28 at -1.0 percent fuel escalation to 1.69 for +5 percent fuel escalation. No escalation sensitivity analysis was performed for a wet year.

Scenario 4

The analysis indicates that the cost of the Powerformer™ with auto-transformer cannot exceed a 1.22 "break-even" multiple of the cost of a conventional generator and transformer to provide a positive benefit-to-cost ratio. The "break-even" multiple drops to 1.05, if the second rewind does not occur in a wet year. The efficiency of the Powerformer™ with auto-transformer combination was found to slightly exceed the conventional generator/transformer combination. The single major factor in this scenario is the total cost of the second rewind of the conventional generator, which includes the disassembly and reassembly cost. Multiples varied with fuel escalation from 0.98 at -1.0 percent fuel escalation to 1.22 for +5 percent fuel escalation. No escalation sensitivity analysis was performed for a wet year.